Computer-Aided Reasoning for Software

CSE507

Solver-Aided Programming I

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Topics

What is this course about?

Course logistics

Getting started with solver-aided programming!

welcome

about

Tools for building better software, more easily

more reliable, efficient, secure

Tools for building **better software**, more easily

Tools for building **better software**, more easily

automated verification, synthesis, debugging, based on satisfiability solvers

Tools for building **better software**, more easily

automated verification, synthesis, debugging, based on satisfiability solvers

"solver-aided tools"

goal

By the end of this course, you'll be able to build solver-aided tools for any domain!

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systems

security

biology

education

networking

hardware

databases

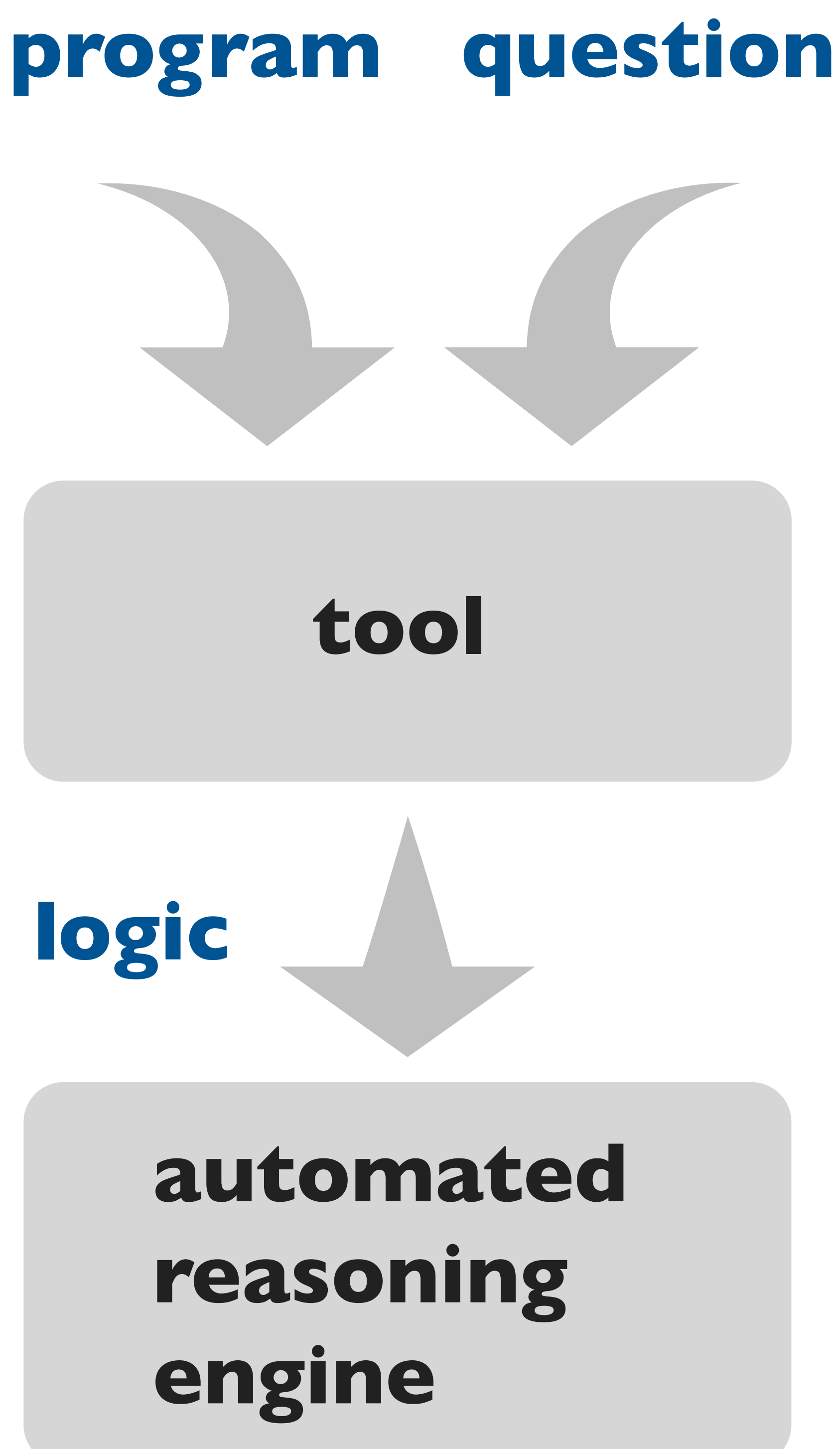
low-power computing

high-performance computing

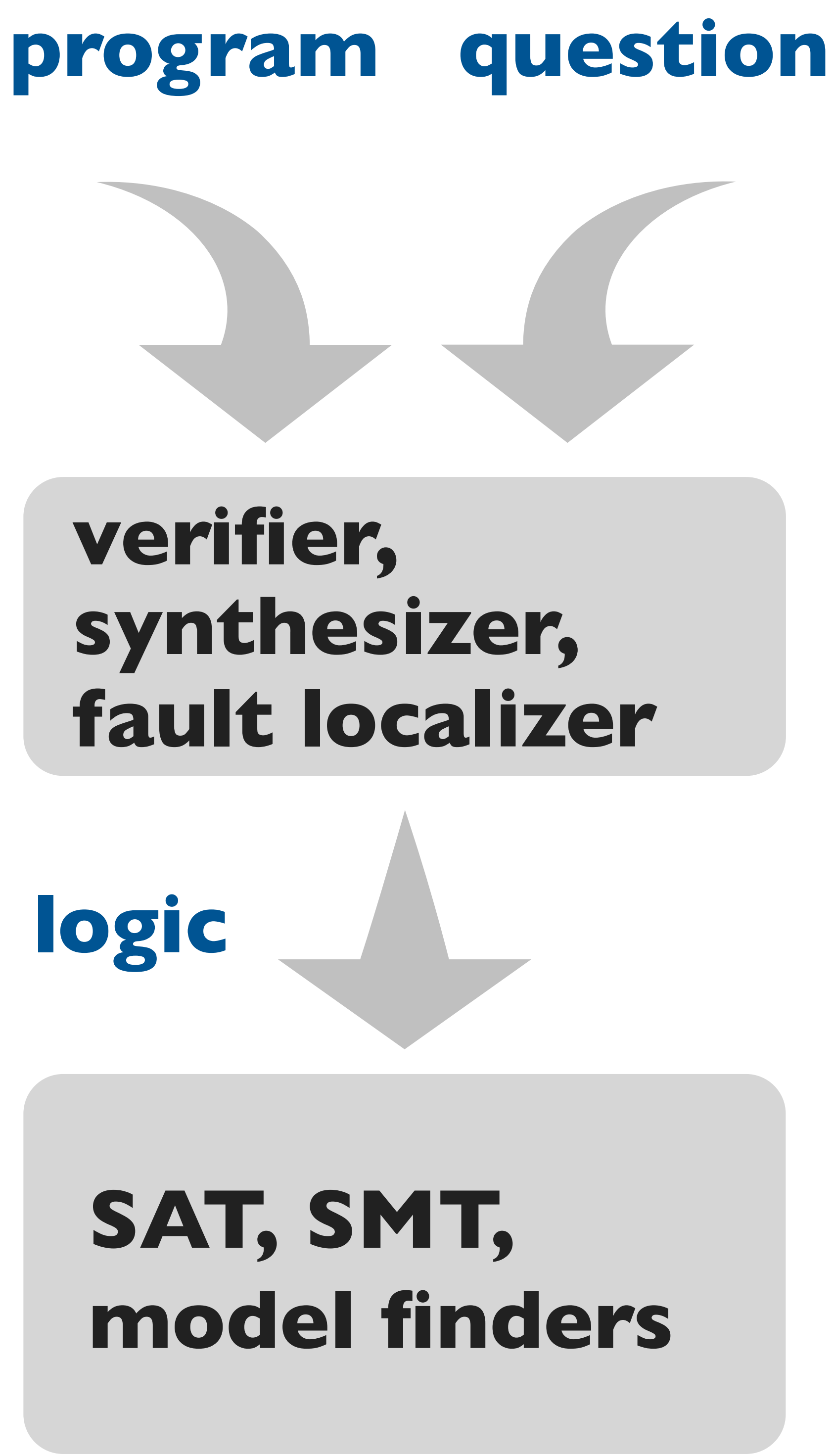
logistics

Topics, structure, people

Course overview



Course overview



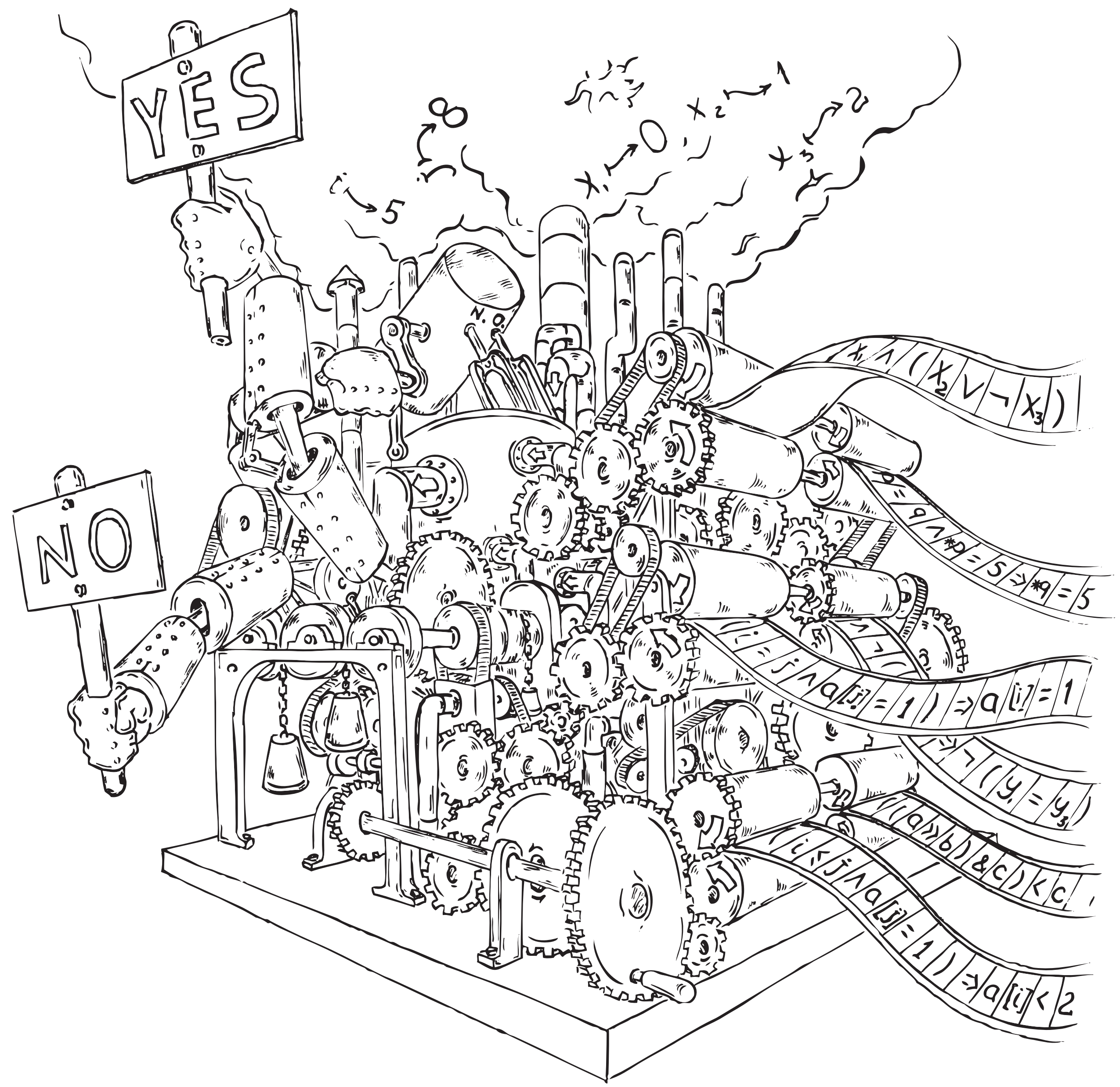
Course overview

program **question**

verifier, synthesizer, fault localizer

logic

SAT, SMT, model finders



Drawing from “Decision Procedures” by Kroening & Strichman

Course overview

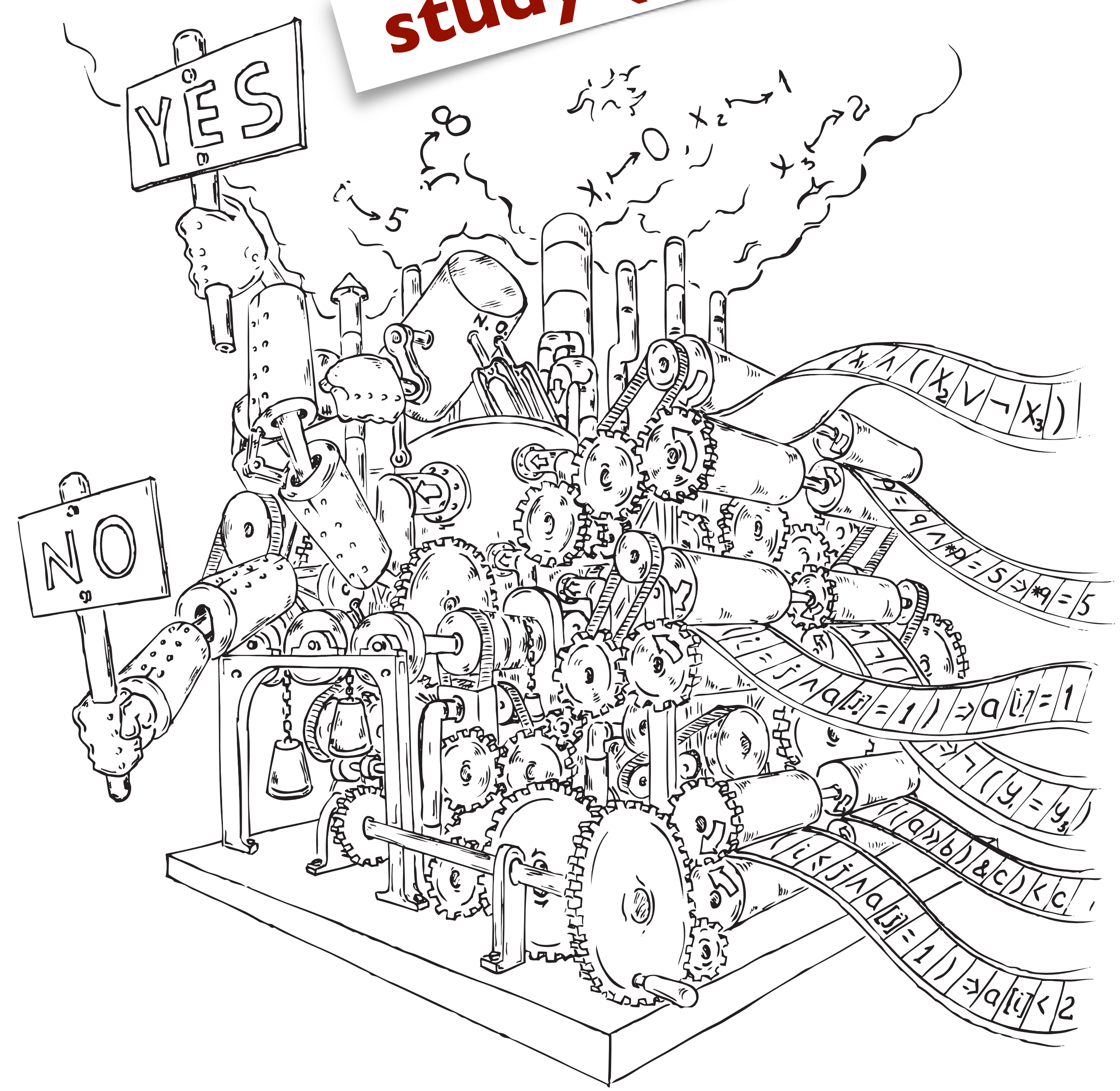
program **question**

verifier, synthesizer, fault localizer

logic

SAT, SMT, model finders

study (part I)



Drawing from "Decision Procedures" by Kroening & Strichman

Course overview

program **question**

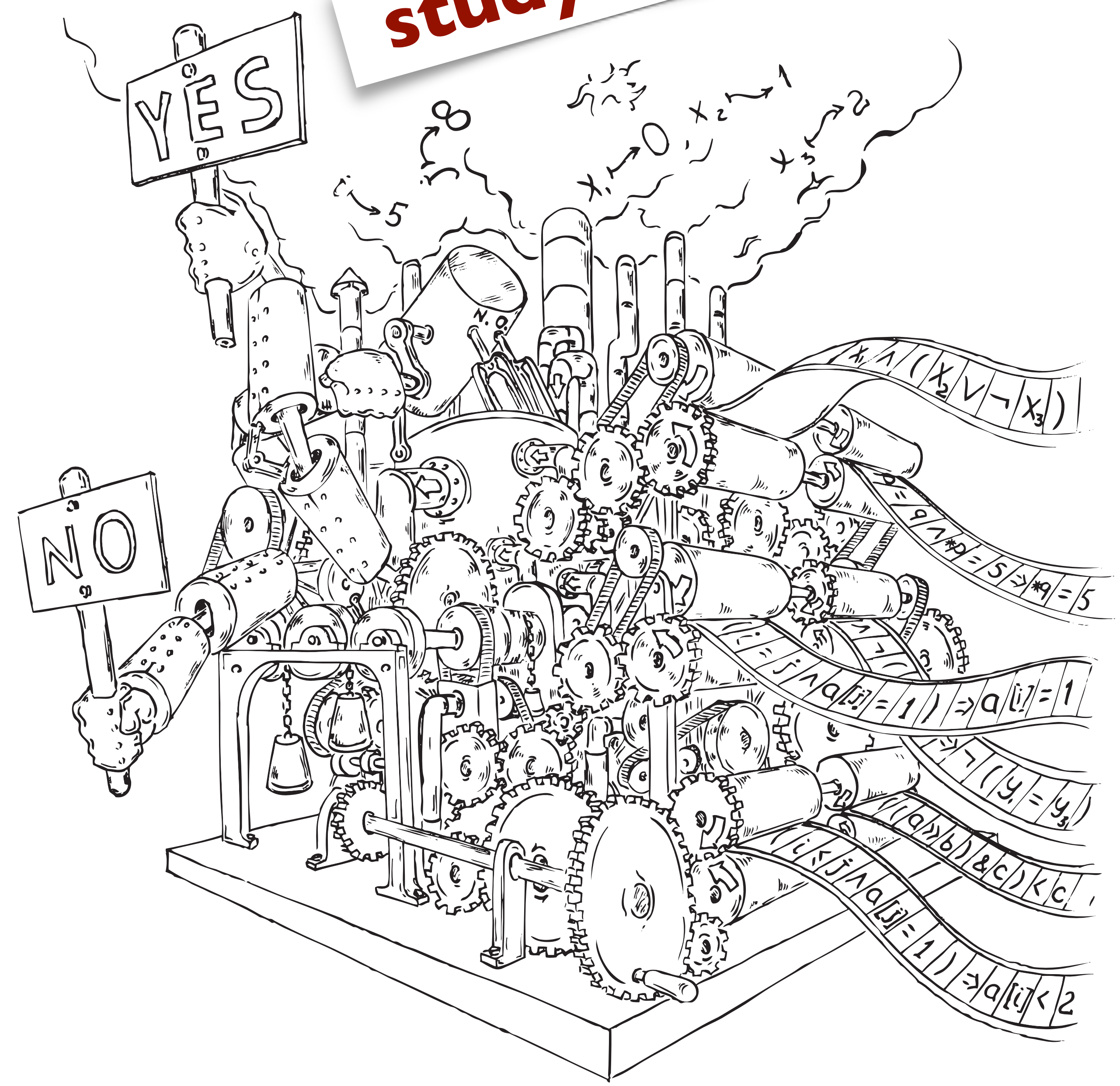
verifier,
synthesizer,
fault localizer

build! (part II)

logic

SAT, SMT,
model finders

study (part I)



Drawing from "Decision Procedures" by Kroening & Strichman

Grading

study (part I)

3 individual homework assignments (75%)

- conceptual problems & proofs (TeX)
- implementations (Racket)
- completed on your own (may discuss HWs with course staff only)

Course project (25%)

- build a computer-aided reasoning tool for a domain of your choice
- teams of 2-3 people
- see the course web page for timeline, deliverables and other details

build! (part II)

Reading and references

Recommended readings posted on the course web page

- Complete each reading before the lecture for which it is assigned
- If multiple papers are listed, only the first is required reading

Recommended text books

- Bradley & Manna, The Calculus of Computation
- Kroening & Strichman, Decision Procedures

Advice for doing well in 507

Come to class (prepared)

- Lecture slides are enough to teach from, but not enough to learn from

Participate

- Ask and answer questions

Meet deadlines

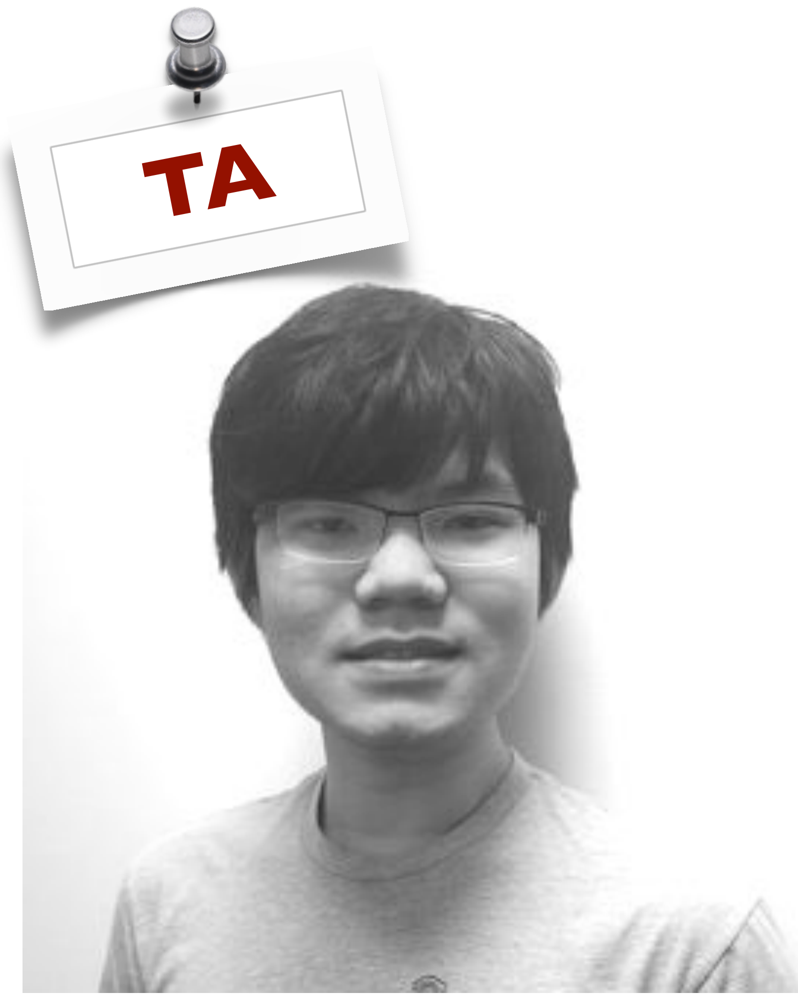
- Turn homework in on time
- Start homework and project sooner than you think you need to
- Follow instructions for submitting code (we have to be able to run it)
- No proof should be longer than a page (most are ~1 paragraph)

People

Emina Torlak
PLSE
CSE 596

Sorawee Porncharoenwase
PLSE
CSE 486
OH Th 2-3pm

People



students!

Your name
Research area

Emina Torlak
PLSE
CSE 596
By appointment

Sorawee Porncharoenwase
PLSE
CSE 486
OH Th 2-3pm

Solver-aided programming in two parts:
(1) getting started and (2) going pro

A programming model that integrates solvers into the language, providing constructs for program verification, synthesis, and more.

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Solver-aided programming in two parts: (1) getting started and (2) going pro

How to use a solver-aided language: the workflow, constructs, and gotchas.

A programming model that integrates solvers into the language, providing constructs for program verification, synthesis, and more.

Solver-aided programming in two parts: (1) getting started and (2) going pro

How to use a solver-aided language: the workflow, constructs, and gotchas.

How to build your own solver-aided tool via direct symbolic evaluation or language embedding.

A programming model that integrates solvers into the language, providing constructs for program verification, synthesis, and more.

ROSETTE

Solver-aided programming in two parts: (1) getting started and (2) going pro

How to use a solver-aided language: the workflow, constructs, and gotchas.

How to build your own solver-aided tool via direct symbolic evaluation or language embedding.

A programming model that integrates solvers into the language, providing constructs for program verification, synthesis, and more.

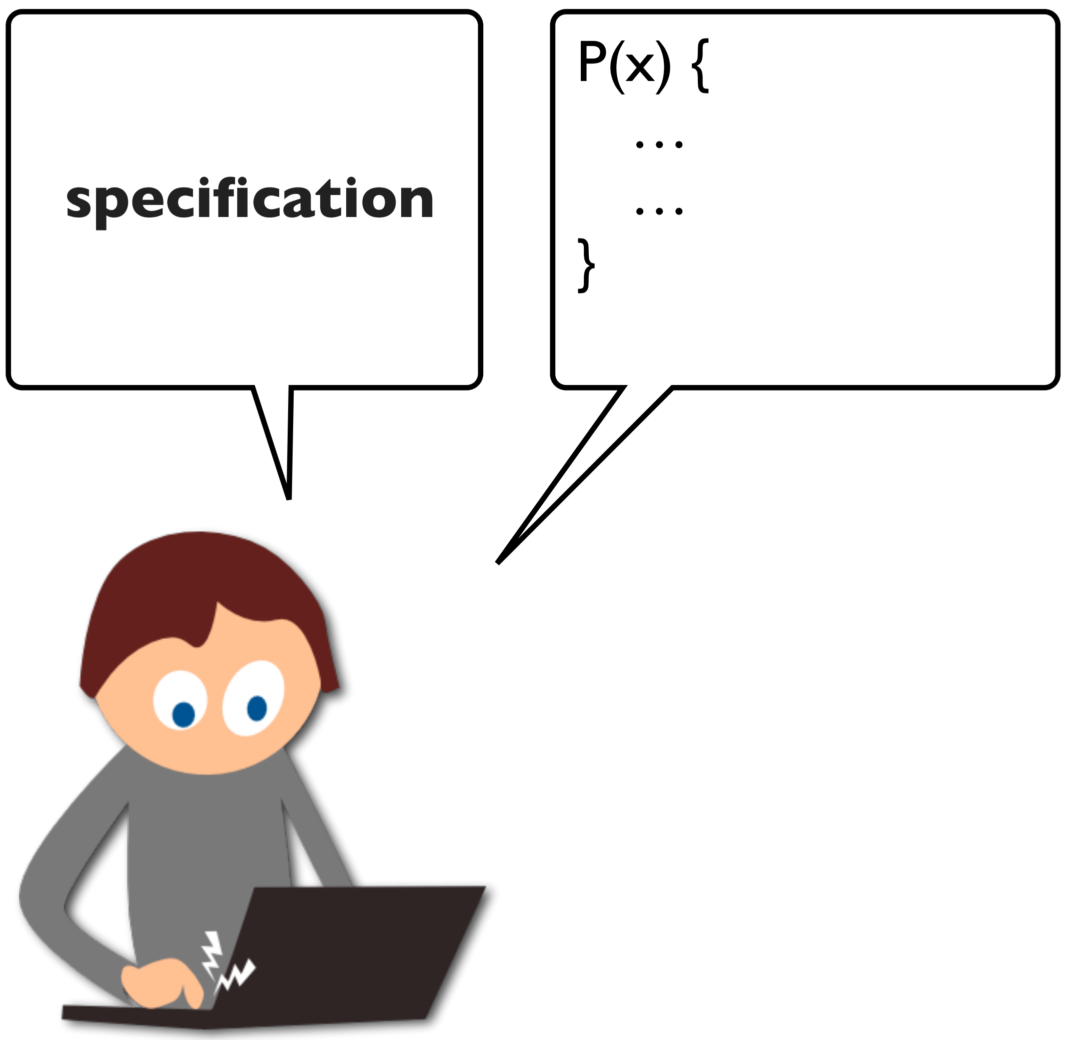
ROSETTE

Solver-aided programming in two parts: (1) **getting started** and (2) going pro

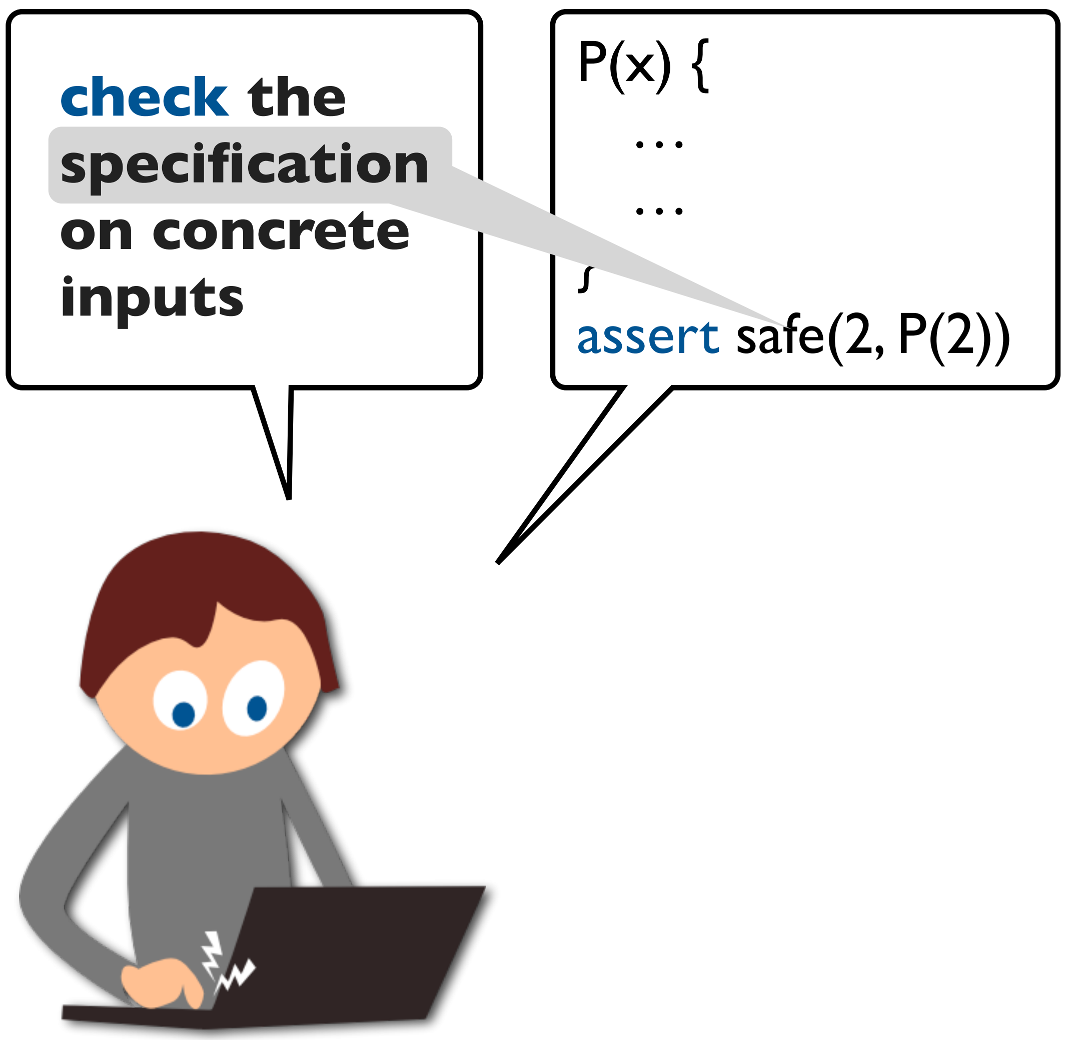
How to use a solver-aided language: the **workflow**, constructs and gotchas.

How to build your own solver-aided tool via direct symbolic evaluation or language embedding.

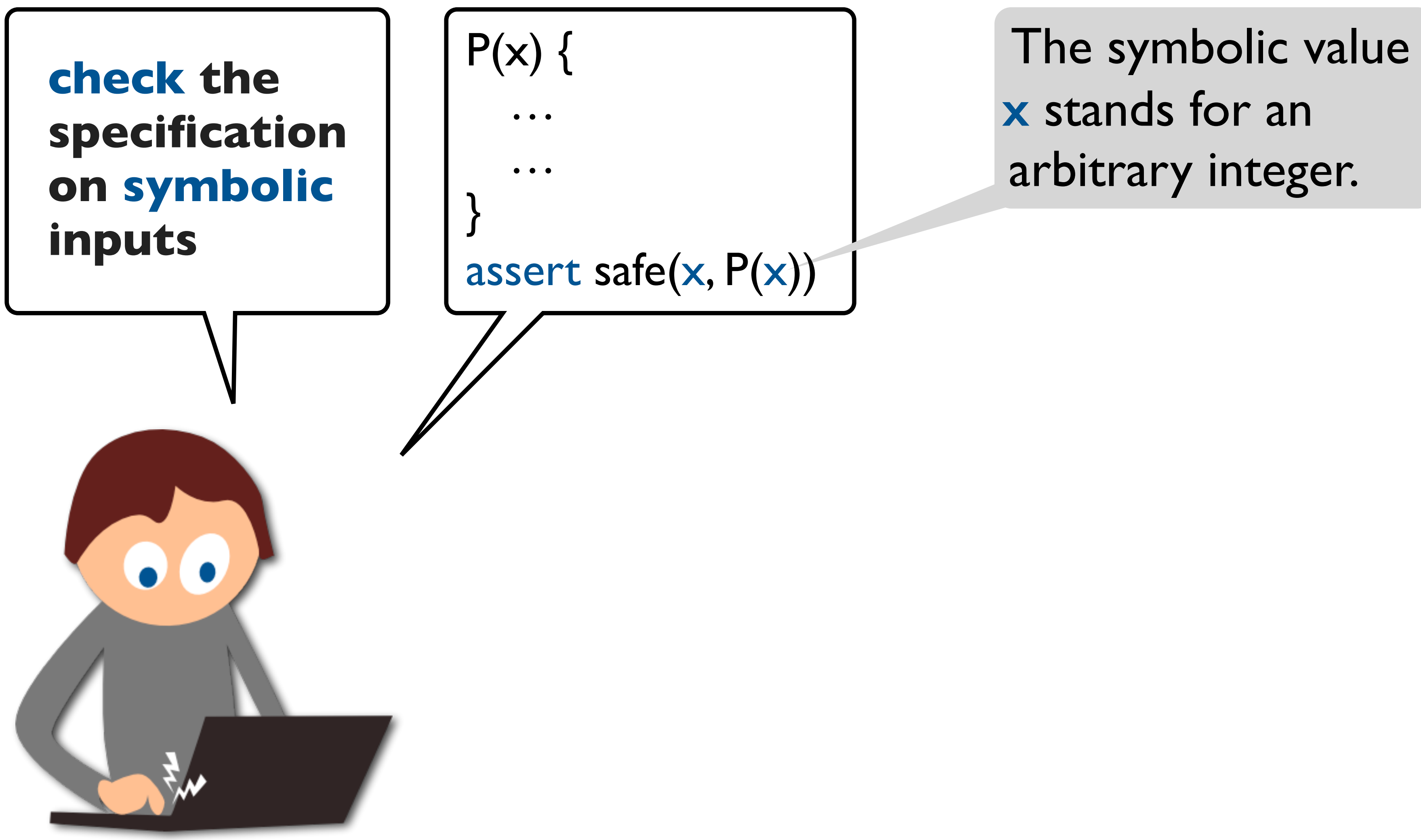
Classic programming: from spec to code



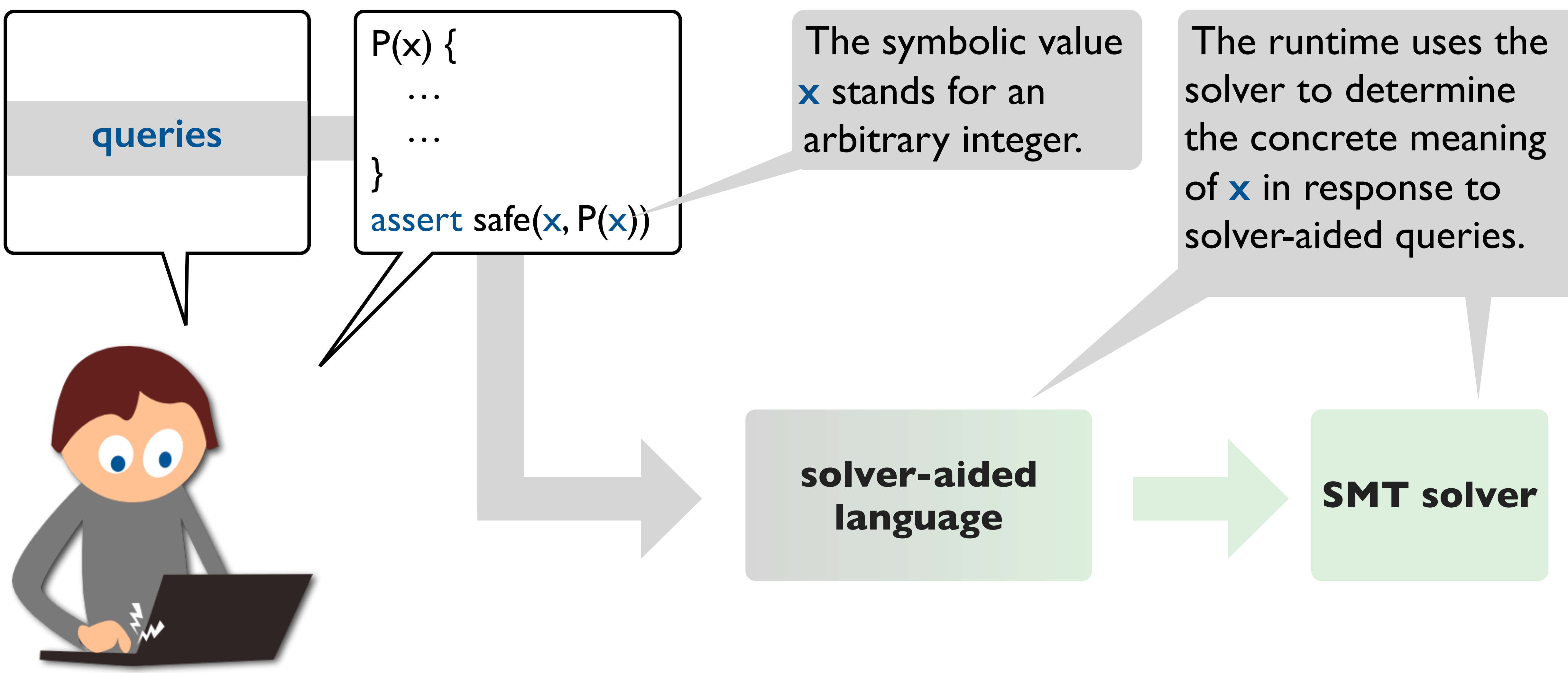
Classic programming: check code against spec



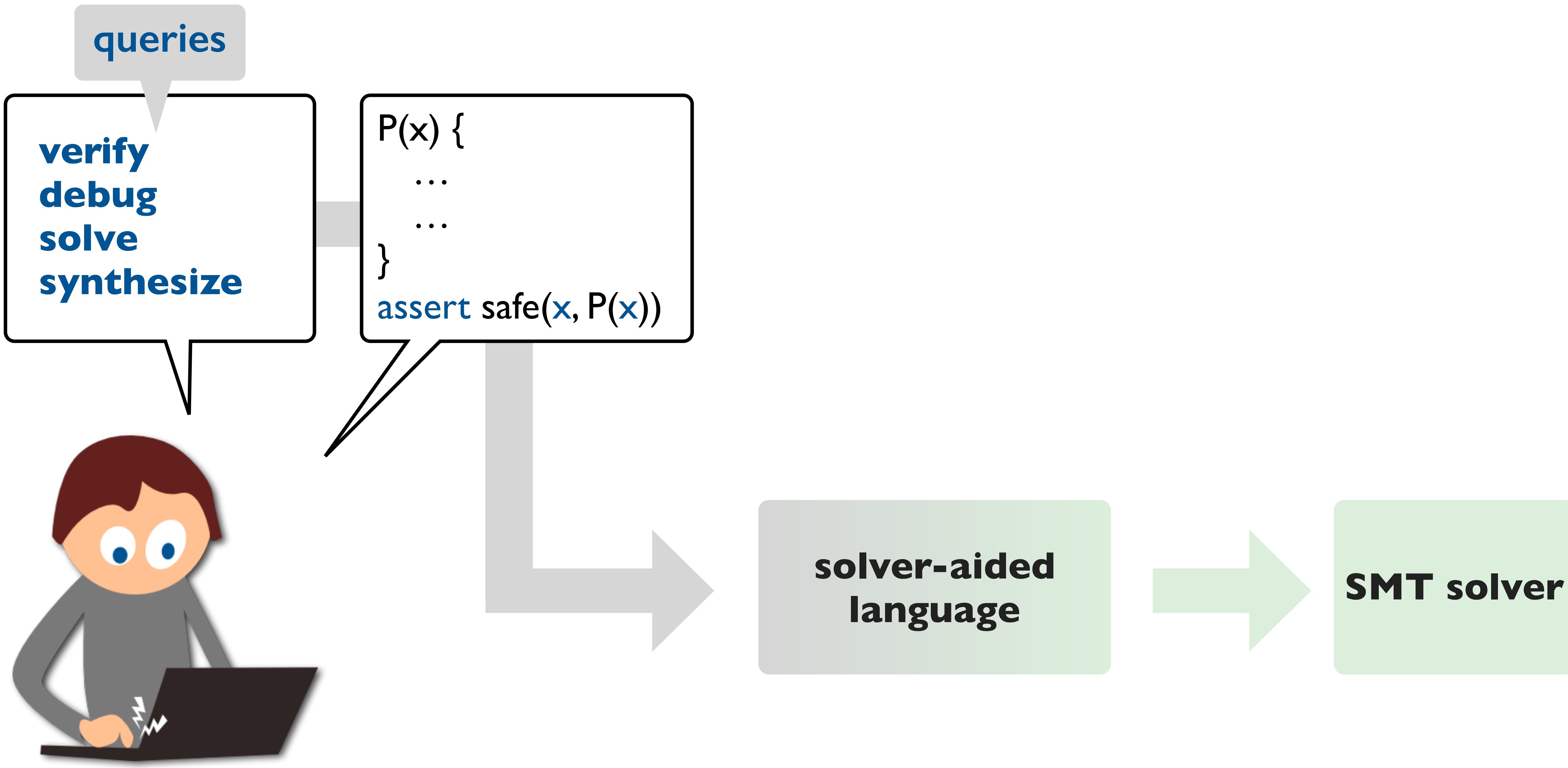
Solver-aided programming: add *symbolic values*



Solver-aided programming: *query* code against spec

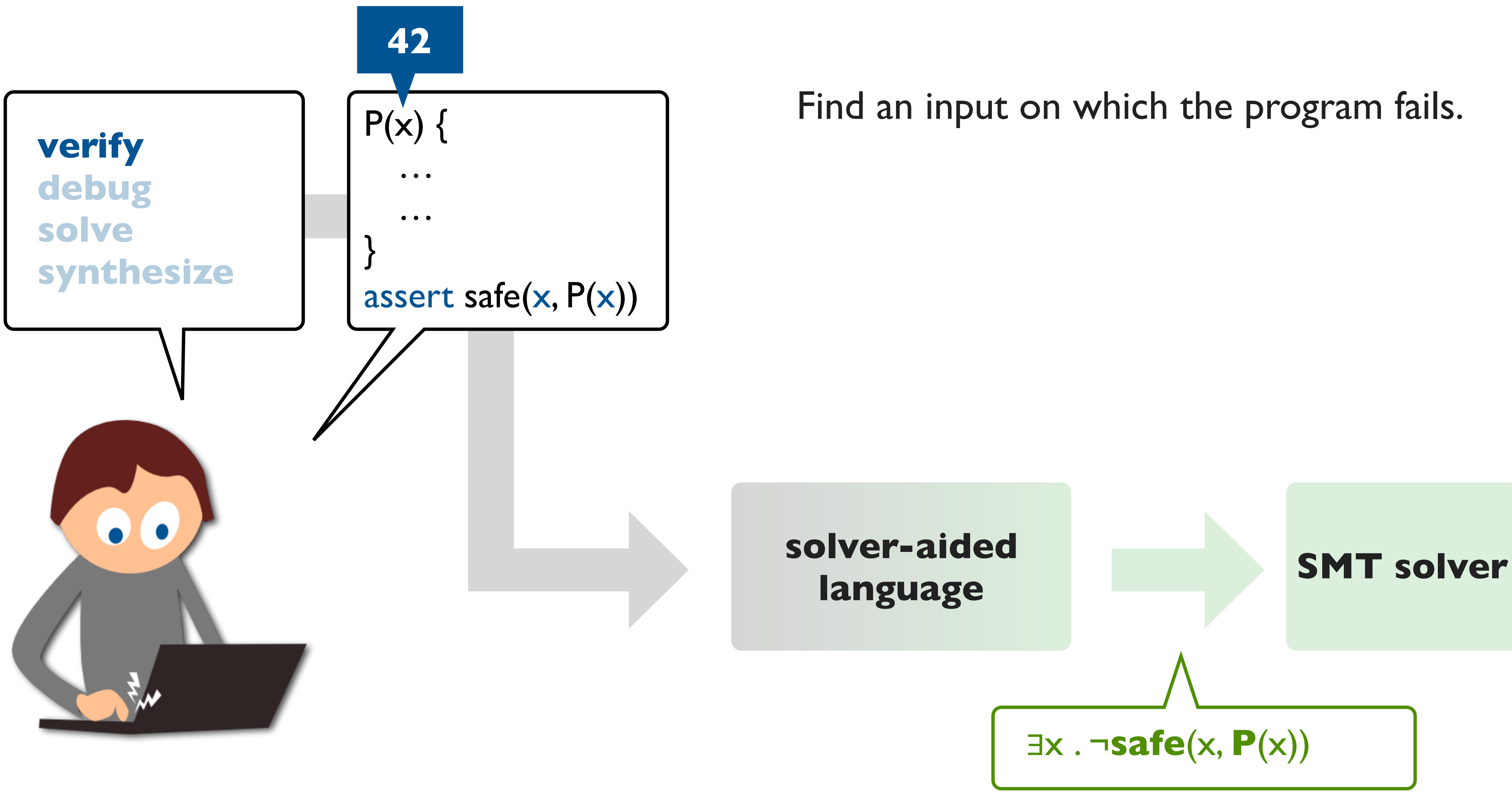


Solver-aided programming: *query* code against spec



Solver-aided programming: *verify* code against spec

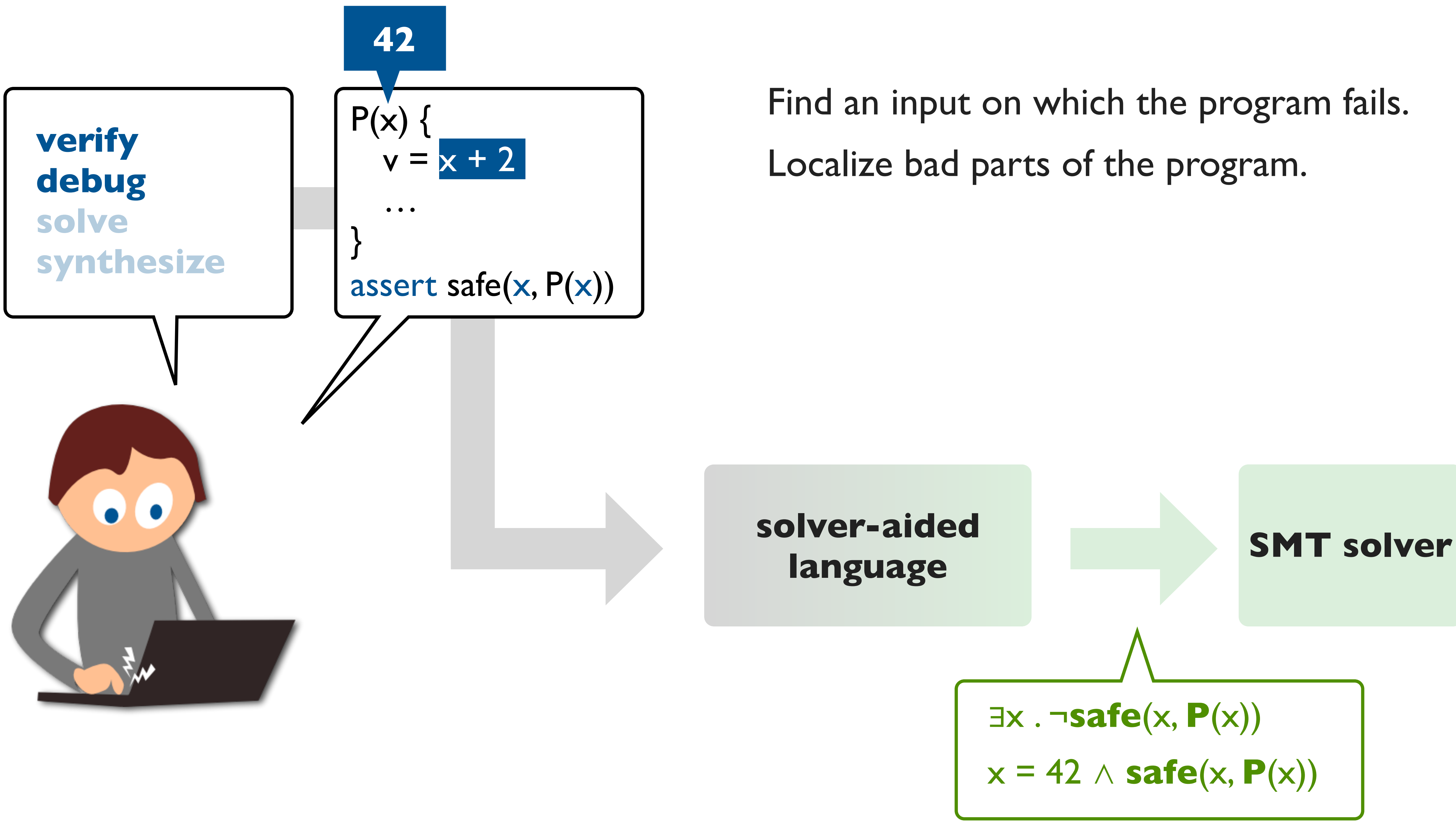
Find an input on which the program fails.



Solver-aided programming: *debug* code against spec

Find an input on which the program fails.

Localize bad parts of the program.

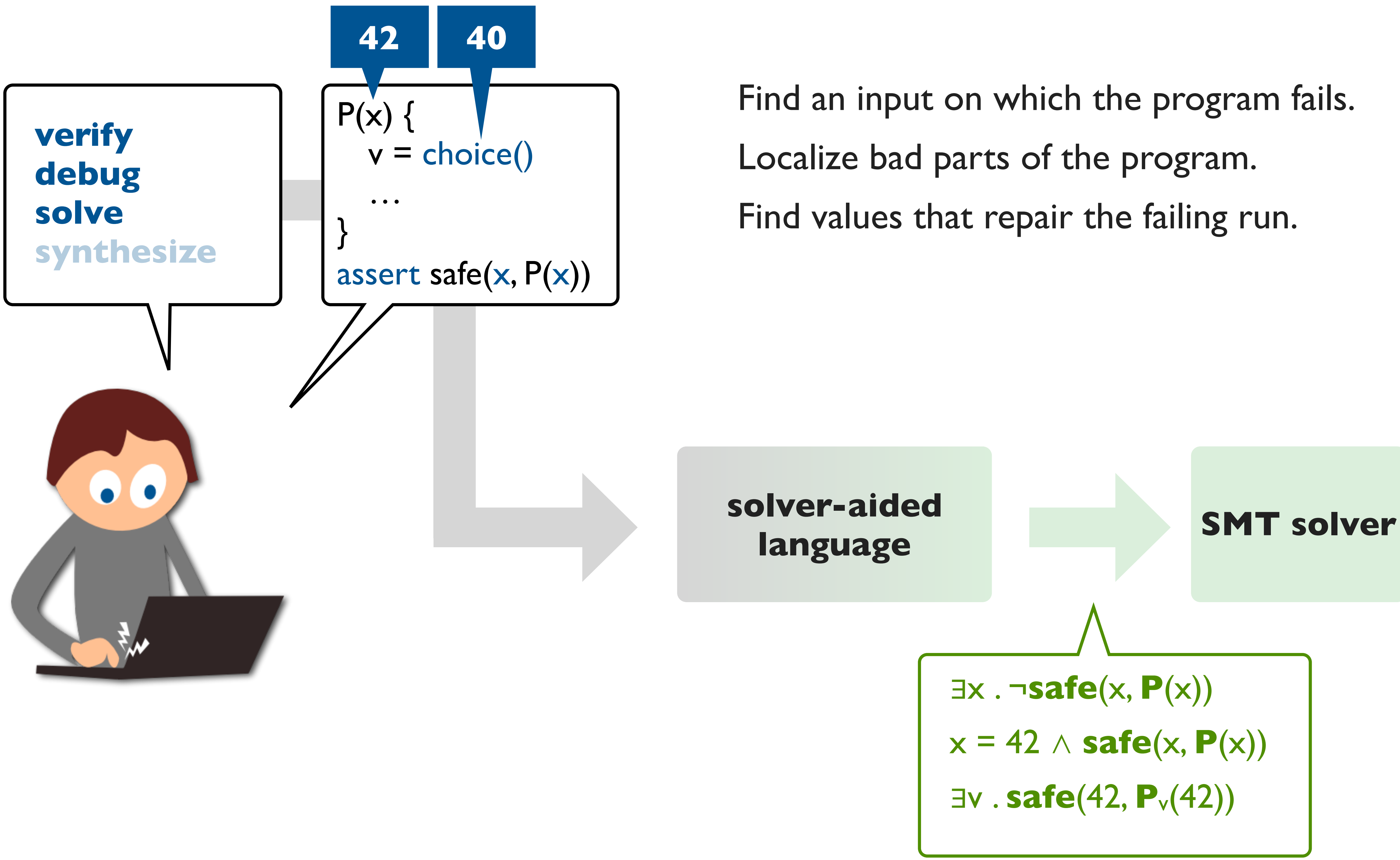


Solver-aided programming: *solve* for values from spec

Find an input on which the program fails.

Localize bad parts of the program.

Find values that repair the failing run.



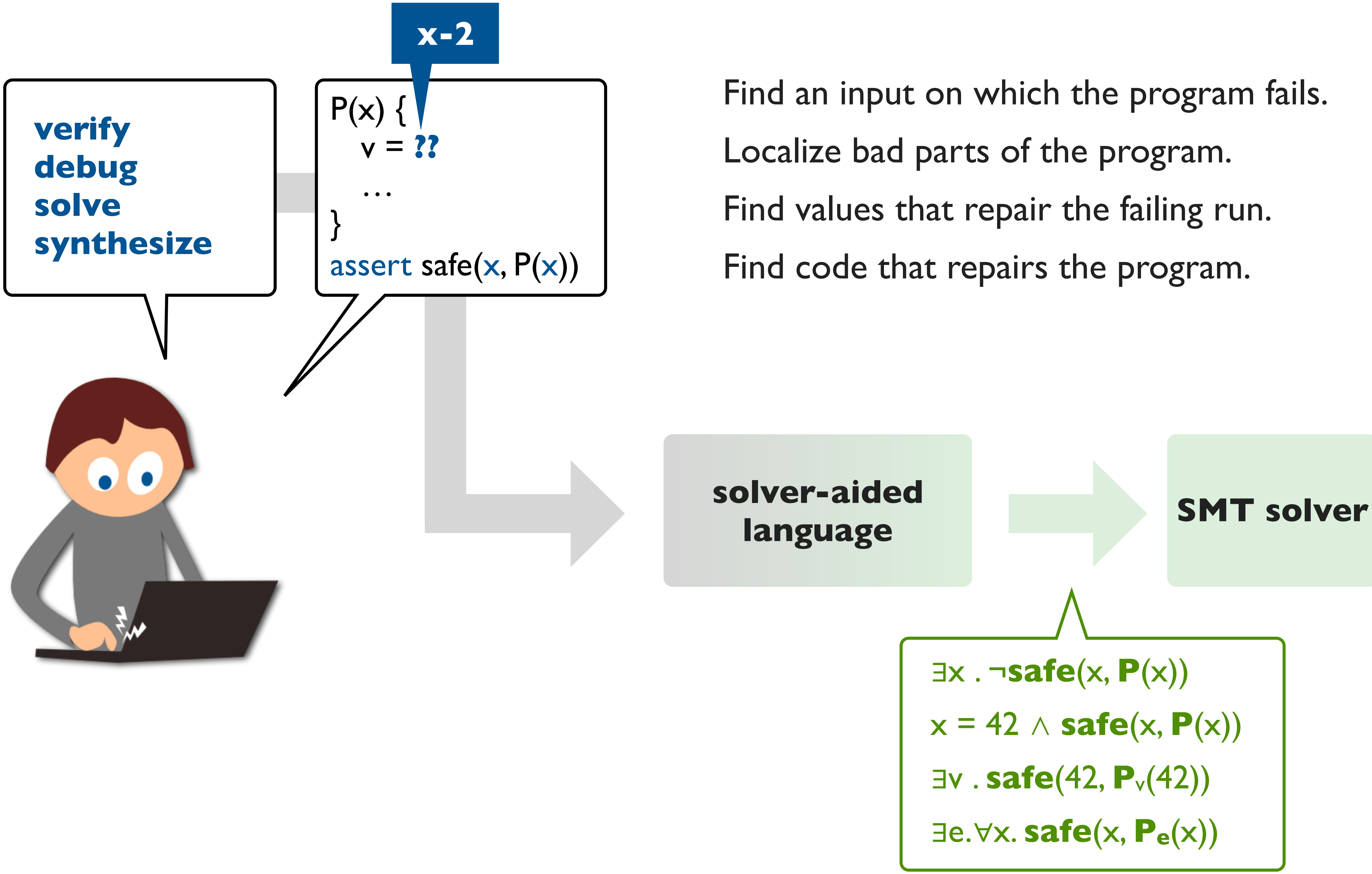
Solver-aided programming: *synthesize* code from spec

Find an input on which the program fails.

Localize bad parts of the program.

Find values that repair the failing run.

Find code that repairs the program.



Solver-aided programming: workflow

Use **assertions** and **symbolic values** to express the specification.

Ask **queries** about program behavior (on arbitrary inputs) with respect to the specification.

verify
debug
solve
synthesize

```
P(x) {
  …
  …
}
assert safe(x, P(x))
```

solver-aided language → **SMT solver**

$\exists x\ .\ \neg \mathbf{safe}(x, \mathbf{P}(x))$

$x = 42 \wedge \mathbf{safe}(x, \mathbf{P}(x))$

$\exists v\ .\ \mathbf{safe}(42, \mathbf{P}_v(42))$

$\exists e. \forall x.\ \mathbf{safe}(x, \mathbf{P}_e(x))$

A programming model that integrates solvers into the language, providing constructs for program verification, synthesis, and more.

ROSETTE

symbolic values
assertions
queries

Solver-aided programming in two parts: (1) **getting started** and (2) going pro

How to use a solver-aided language: the workflow, **constructs**, and gotchas.

How to build your own solver-aided tool via direct symbolic evaluation or language embedding.

Rosette extends Racket with solver-aided constructs

= +

```
(define-symbolic id type)
(define-symbolic* id type)
```

symbolic values

```
(assert expr)
```

assertions

```
(verify expr)
(debug [type ...+] expr)
(solve expr)
(synthesize
  #:forall expr
  #:guarantee expr)
```

queries

Rosette extends **Racket** with solver-aided constructs

"A programming language for creating new programming languages"

= +

A modern descendent of Scheme and Lisp with powerful macro-based meta programming.

```
(define-symbolic id type)
(define-symbolic* id type)
```

symbolic values

```
(assert expr)
```

assertions

```
(verify expr)
(debug [type ...+] expr)
(solve expr)
(synthesize
  #:forall expr
  #:guarantee expr)
```

queries

Rosette extends **Racket** with solver-aided constructs

```
#lang rosette
```

= +

```
#lang racket
```

```
(define-symbolic id type)
(define-symbolic* id type)
```

symbolic values

```
(assert expr)
```

assertions

```
(verify expr)
(debug [type ...+] expr)
(solve expr)
(synthesize
  #:forall expr
  #:guarantee expr)
```

queries

Rosette constructs: define-symbolic

```
(define-symbolic id type)
(define-symbolic* id type)

(assert expr)

(verify expr)
(debug [type ...+] expr)
(solve expr)
(synthesize
  #:forall expr
  #:guarantee expr)
```

define-symbolic creates a fresh symbolic *constant* of the given type and binds it to the variable id.

```
> (define-symbolic x integer?)
```

Rosette constructs: define-symbolic

A type that is efficiently supported by SMT solvers: booleans, integers, reals, bitvectors, uninterpreted functions.

```
(define-symbolic id type)
(define-symbolic* id type)
```

```
(assert expr)
```

```
(verify expr)
(debug [type ...+] expr)
(solve expr)
(synthesize
  #:forall expr
  #:guarantee expr)
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```
(define-symbolic id type)
(define-symbolic* id type)

(assert expr)

(verify expr)
(debug [type ...+] expr)
(solve expr)
(synthesize
  #:forall expr
  #:guarantee expr)
```

define-symbolic creates a fresh symbolic *constant* of the given type and binds it to the variable id.

```
> (define-symbolic x integer?)
> (+ 1 x 2 3)
(+ 6 x)
```

Symbolic values of a given type can be used just like concrete values of that type.

Rosette constructs: define-symbolic

A type that is efficiently supported by SMT solvers: booleans, integers, reals, bitvectors, uninterpreted functions.

```
(define-symbolic id type)
(define-symbolic* id type)

(assert expr)

(verify expr)
(debug [type ...+] expr)
(solve expr)
(synthesize
  #:forall expr
  #:guarantee expr)
```

define-symbolic creates a fresh symbolic *constant* of the given type and binds it to the variable id.

```
> (define (same-x)
    (define-symbolic x integer?)
    x)
> (same-x)
x
> (same-x)
x
> (eq? (same-x) (same-x))
#t
```

id is bound to the *same* constant every time **define-symbolic** is evaluated.

Symbolic values of a given type can be used just like concrete values of that type.

Rosette constructs: define-symbolic*

A type that is efficiently supported by SMT solvers: booleans, integers, reals, bitvectors, uninterpreted functions.

```
(define-symbolic id type)
(define-symbolic* id type)
```

```
(assert expr)
```

```
(verify expr)
(debug [type ...+] expr)
(solve expr)
(synthesize
  #:forall expr
  #:guarantee expr)
```

define-symbolic* creates a fresh symbolic *constant* of the given type and binds it to the variable id.

```
> (define (new-x)
    (define-symbolic* x integer?)
    x)
> (new-x)
x$0
> (new-x)
x$1
> (eq? (new-x) (new-x))
(= x$2 x$3)
```

id is bound to a *different* constant every time **define-symbolic*** is evaluated.

Symbolic values of a given type can be used just like concrete values of that type.

Rosette constructs: creating complex symbolic values

```
(define-symbolic id type)
(define-symbolic* id type)
```

```
(assert expr)
```

```
(verify expr)
(debug [type ...+] expr)
(solve expr)
(synthesize
  #:forall expr
  #:guarantee expr)
```

define-symbolic(*) can be used to create *bounded* symbolic instances of complex data types.

Rosette constructs: creating complex symbolic values

```
(define-symbolic id type)
(define-symbolic* id type)
```

```
(assert expr)
```

```
(verify expr)
(debug [type ...+] expr)
(solve expr)
(synthesize
  #:forall expr
  #:guarantee expr)
```

define-symbolic(*) can be used to create *bounded* symbolic instances of complex data types.

```
> (define-symbolic* xs integer? [4])
> xs
(list xs$0 xs$1 xs$2 xs$3)
```

A concrete list of 4 symbolic integers; this is just a short-hand for evaluating **define-symbolic*** 4 times and collecting the results into a list.

Rosette constructs: creating complex symbolic values

```
(define-symbolic id type)
(define-symbolic* id type)
```

```
(assert expr)
```

```
(verify expr)
(debug [type ...+] expr)
(solve expr)
(synthesize
  #:forall expr
  #:guarantee expr)
```

define-symbolic(*) can be used to create *bounded* symbolic instances of complex data types.

```
> (define-symbolic* xs integer? [4])
> xs
(list xs$0 xs$1 xs$2 xs$3)
> (define-symbolic* len integer?)
> (take xs len)
{[(= 0 len$0) ()]
 [(= 1 len$0) (xs$0)]
 [(= 2 len$0) (xs$0 xs$1)]
 [(= 3 len$0) (xs$0 xs$1 xs$2)]
 [(= 4 len$0) (xs$0 xs$1 xs$2 xs$3)]}
```

A symbolic list of length up to 4, consisting of symbolic integers.

Rosette constructs: assert

```
(define-symbolic id type)
(define-symbolic* id type)
```

```
(assert expr)
```

```
(verify expr)
(debug [type ...+] expr)
(solve expr)
(synthesize
  #:forall expr
  #:guarantee expr)
```

assert checks that expr evaluates to a true value.

```
> (assert (>= 2 1)) ; passes
> (assert (< 2 1))  ; fails
assert: failed
```

Rosette constructs: assert

```
(define-symbolic id type)
(define-symbolic* id type)
```

```
(assert expr)
```

```
(verify expr)
(debug [type ...+] expr)
(solve expr)
(synthesize
  #:forall expr
  #:guarantee expr)
```

assert checks that expr evaluates to a true value.

```
> (assert (>= 2 1)) ; passes
> (assert (< 2 1))  ; fails
assert: failed
```

```
> (define-symbolic* x integer?)
> (assert (>= x 1))
```

Symbolic expr gets added to the assertion store. Its meaning (true or false) is eventually determined by the solver in response to queries.

Rosette constructs: assert

```
(define-symbolic id type)
(define-symbolic* id type)
```

```
(assert expr)
```

```
(verify expr)
(debug [type ...+] expr)
(solve expr)
(synthesize
  #:forall expr
  #:guarantee expr)
```

assert checks that expr evaluates to a true value.

```
> (assert (>= 2 1)) ; passes
> (assert (< 2 1))  ; fails
assert: failed
```

```
> (define-symbolic* x integer?)
> (assert (>= x 1))
> (asserts)
(list (<= 1 x$0) ...)
```

Symbolic expr gets added to the assertion store. Its meaning (true or false) is eventually determined by the solver in response to queries.

Rosette constructs: from assert to verify

```
(define-symbolic id type)
(define-symbolic* id type)
```

```
(assert expr)
```

```
(verify expr)
(debug [type ...+] expr)
(solve expr)
(synthesize
  #:forall expr
  #:guarantee expr)
```

Do poly and fact produce the same output on all inputs?

```
(define (poly x)
 (+ (* x x x x) (* 6 x x x)
    (* 11 x x) (* 6 x)))

(define (fact x)
 (* x (+ x 1) (+ x 2) (+ x 2)))

(define (same p f x)
 (assert (= (p x) (f x))))


; some tests ...
> (same poly fact 0)  ; pass
> (same poly fact -1) ; pass
> (same poly fact -2) ; pass
```

Rosette constructs: verify

verify searches for a binding of symbolic constants to concrete values that causes at least one assertion in expr to fail.

```
(define-symbolic id type)
(define-symbolic* id type)
```

```
(assert expr)
```

```
(verify expr)
(debug [type ...+] expr)
(solve expr)
(synthesize
  #:forall expr
  #:guarantee expr)
```

Do `poly` and `fact` produce the same output on all inputs?

```
(define (poly x)
 (+ (* x x x x) (* 6 x x x)
    (* 11 x x) (* 6 x)))

(define (fact x)
 (* x (+ x 1) (+ x 2) (+ x 2)))

(define (same p f x)
 (assert (= (p x) (f x))))


; some tests ...
> (same poly fact 0)  ; pass
> (same poly fact -1) ; pass
> (same poly fact -2) ; pass
```

Rosette constructs: verify

verify searches for a binding of symbolic constants to concrete values that causes at least one assertion in expr to fail.

```
(define-symbolic id type)
(define-symbolic* id type)
```

```
(assert expr)
```

```
(verify expr)
(debug [type ...+] expr)
(solve expr)
(synthesize
  #:forall expr
  #:guarantee expr)
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Do poly and fact produce the same output on all inputs?

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(define (poly x)
 (+ (* x x x x) (* 6 x x x)
    (* 11 x x) (* 6 x)))

(define (fact x)
 (* x (+ x 1) (+ x 2) (+ x 2)))

(define (same p f x)
 (assert (= (p x) (f x))))


> (define-symbolic i integer?)
> (verify (same poly fact i)))
```

Rosette constructs: verify

verify searches for a binding of symbolic constants to concrete values that causes at least one assertion in expr to fail.

```
(define-symbolic id type)
(define-symbolic* id type)
```

```
(assert expr)
```

```
(verify expr)
(debug [type ...+] expr)
(solve expr)
(synthesize
  #:forall expr
  #:guarantee expr)
```

No! The solver finds a concrete *counterexample* to the assertion in same.

Do poly and fact produce the same output on all inputs?

```
(define (poly x)
 (+ (* x x x x) (* 6 x x x)
    (* 11 x x) (* 6 x)))

(define (fact x)
 (* x (+ x 1) (+ x 2) (+ x 2)))

(define (same p f x)
 (assert (= (p x) (f x))))


> (define-symbolic i integer?)
> (verify (same poly fact i))
(model [i -6])
```

Rosette constructs: verify

verify searches for a binding of symbolic constants to concrete values that causes at least one assertion in expr to fail.

```
(define-symbolic id type)
(define-symbolic* id type)
```

```
(assert expr)
```

```
(verify expr)
(debug [type ...+] expr)
(solve expr)
(synthesize
  #:forall expr
  #:guarantee expr)
```

We can store bindings in variables and evaluate arbitrary expressions against them.

Do `poly` and `fact` produce the same output on all inputs?

```
(define (poly x)
 (+ (* x x x x) (* 6 x x x)
    (* 11 x x) (* 6 x)))

(define (fact x)
 (* x (+ x 1) (+ x 2) (+ x 2)))

(define (same p f x)
 (assert (= (p x) (f x))))


> (define-symbolic i integer?)
> (define cex
    (verify (same poly fact i)))
> (evaluate i cex)
-6
```

Rosette constructs: verify

verify searches for a binding of symbolic constants to concrete values that causes at least one assertion in expr to fail.

```
(define-symbolic id type)
(define-symbolic* id type)
```

```
(assert expr)
```

```
(verify expr)
(debug [type ...+] expr)
(solve expr)
(synthesize
  #:forall expr
  #:guarantee expr)
```

The assertions encountered while evaluating expr are removed from the asserts store once a query (such as **verify**) completes.

Do `poly` and `fact` produce the same output on all inputs?

```
(define (poly x)
 (+ (* x x x x) (* 6 x x x)
    (* 11 x x) (* 6 x)))

(define (fact x)
 (* x (+ x 1) (+ x 2) (+ x 2)))

(define (same p f x)
 (assert (= (p x) (f x))))


> (define-symbolic i integer?)
> (define cex
    (verify (same poly fact i)))
> (asserts)
(list)
```

Rosette constructs: from verify to debug

```
(define-symbolic id type)
(define-symbolic* id type)
```

```
(assert expr)
```

```
(verify expr)
(debug [type ...+] expr)
(solve expr)
(synthesize
  #:forall expr
  #:guarantee expr)
```

Why do `poly` and `fact` output different values on the input -6?

```
(define (poly x)
 (+ (* x x x x) (* 6 x x x)
    (* 11 x x) (* 6 x)))

(define (fact x)
 (* x (+ x 1) (+ x 2) (+ x 2)))

(define (same p f x)
 (assert (= (p x) (f x))))
```

Rosette constructs: from verify to debug

debug searches for a minimal set of expressions of the given types that cause the evaluation of expr to fail.

```
(define-symbolic id type)
(define-symbolic* id type)
```

```
(assert expr)
```

```
(verify expr)
(debug [type ...+] expr)
(solve expr)
(synthesize
  #:forall expr
  #:guarantee expr)
```

Why do poly and fact output different values on the input -6?

```
(define (poly x)
 (+ (* x x x x) (* 6 x x x)
    (* 11 x x) (* 6 x)))

(define (fact x)
 (* x (+ x 1) (+ x 2) (+ x 2)))

(define (same p f x)
 (assert (= (p x) (f x))))
```

Rosette constructs: debug

debug searches for a minimal set of expressions of the given types that cause the evaluation of expr to fail.

```
(define-symbolic id type)
(define-symbolic* id type)
```

```
(assert expr)
```

```
(verify expr)
(debug [type ...+] expr)
(solve expr)
(synthesize
  #:forall expr
  #:guarantee expr)
```

To use **debug**, require the debugging libraries, mark `fact` as the candidate for debugging, save the module to a file, and issue a **debug** query.

Why do `poly` and `fact` output different values on the input -6?

```
(require rosette/query/debug
         rosette/lib/render)

(define (poly x)
 (+ (* x x x x) (* 6 x x x)
    (* 11 x x) (* 6 x)))

(define/debug (fact x)
 (* x (+ x 1) (+ x 2) (+ x 2)))

(define (same p f x)
 (assert (= (p x) (f x))))
```

```
> (render ; visualize the result
   (debug [integer?]
     (same poly fact -6)))
```

Rosette constructs: debug

debug searches for a minimal set of expressions of the given types that cause the evaluation of expr to fail.

```
(define-symbolic id type)
(define-symbolic* id type)
```

```
(assert expr)
```

```
(verify expr)
(debug [type ...+] expr)
(solve expr)
(synthesize
  #:forall expr
  #:guarantee expr)
```

To use **debug**, require the debugging libraries, mark `fact` as the candidate for debugging, save the module to a file, and issue a **debug** query.

Why do `poly` and `fact` output different values on the input -6?

```
(require rosette/query/debug
         rosette/lib/render)

(define (poly x)
 (+ (* x x x x) (* 6 x x x)
    (* 11 x x) (* 6 x)))

(define/debug (fact x)
 (* x (+ x 1) (+ x 2) (+ x 2)))

(define (same p f x)
 (assert (= (p x) (f x))))
```

```
> (render ; visualize the result
   (debug [integer?]
     (same poly fact -6)))
```

Rosette constructs: from debug to solve

```
(define-symbolic id type)
(define-symbolic* id type)
```

```
(assert expr)
```

```
(verify expr)
(debug [type ...+] expr)
(solve expr)
(synthesize
  #:forall expr
  #:guarantee expr)
```

Can we repair `fact` on the input -6 as suggested by **debug**?

```
(define (poly x)
 (+ (* x x x x) (* 6 x x x)
    (* 11 x x) (* 6 x)))

(define (fact x)
 (* x (+ x 1) (+ x 2) (+ x 2)))

(define (same p f x)
 (assert (= (p x) (f x))))
```

Rosette constructs: from debug to solve

solve searches for a binding of symbolic constants to concrete values that causes all assertions in expr to pass.

```
(define-symbolic id type)
(define-symbolic* id type)
```

```
(assert expr)
```

```
(verify expr)
(debug [type ...+] expr)
(solve expr)
(synthesize
  #:forall expr
  #:guarantee expr)
```

Can we repair `fact` on the input **-6** as suggested by **debug**?

```
(define (poly x)
 (+ (* x x x x) (* 6 x x x)
    (* 11 x x) (* 6 x)))

(define (fact x)
 (* x (+ x 1) (+ x 2) (+ x 2)))

(define (same p f x)
 (assert (= (p x) (f x))))
```

Rosette constructs: solve

solve searches for a binding of symbolic constants to concrete values that causes all assertions in expr to pass.

```
(define-symbolic id type)
(define-symbolic* id type)
```

```
(assert expr)
```

```
(verify expr)
(debug [type ...+] id expr)
(solve expr)
(synthesize
  #:forall expr
  #:guarantee expr)
```

Can we repair fact on the input -6 as suggested by **debug**?

```
(define (poly x)
 (+ (* x x x x) (* 6 x x x)
    (* 11 x x) (* 6 x)))

(define (fact x)
 (define-symbolic* c1 c2 c3 integer?)
 (* (+ x c1) (+ x 1) (+ x c2) (+ x c3)))

(define (same p f x)
 (assert (= (p x) (f x))))


> (solve (same poly fact -6))
```

Rosette constructs: solve

solve searches for a binding of symbolic constants to concrete values that causes all assertions in expr to pass.

```
(define-symbolic id type)
(define-symbolic* id type)
```

```
(assert expr)
```

```
(verify expr)
(debug [type ...+] expr)
(solve expr)
(synthesize
  #:forall expr
  #:guarantee expr)
```

Yes! The solver finds concrete values for c1, c2, and c3 that work for the input -6.

Can we repair fact on the input -6 as suggested by **debug**?

```
(define (poly x)
 (+ (* x x x x) (* 6 x x x)
    (* 11 x x) (* 6 x)))

(define (fact x)
 (define-symbolic* c1 c2 c3 integer?)
 (* (+ x c1) (+ x 1) (+ x c2) (+ x c3)))

(define (same p f x)
 (assert (= (p x) (f x))))


> (solve (same poly fact -6))
(model [c1$0 -66] [c2$0 7] [c3$0 7])
```

Rosette constructs: solve many with define-symbolic*

solve searches for a binding of symbolic constants to concrete values that causes all assertions in expr to pass.

```
(define-symbolic id type)
(define-symbolic* id type)
```

```
(assert expr)
```

```
(verify expr)
(debug [type ...+] expr)
(solve expr)
(synthesize
  #:forall expr
  #:guarantee expr)
```

Solving same for multiple inputs: note the behavior of **define-symbolic***.

Can we repair fact on multiple inputs individually?

```
(define (poly x)
 (+ (* x x x x) (* 6 x x x)
    (* 11 x x) (* 6 x)))

(define (fact x)
 (define-symbolic* c1 c2 c3 integer?)
 (* (+ x c1) (+ x 1) (+ x c2) (+ x c3)))

(define (same p f x)
 (assert (= (p x) (f x))))


> (solve (begin
          (same poly fact -6)
          (same poly fact 12)))
(model [c1$1 -66] [c2$1 7] [c3$1 7]
       [c1$2 2508] [c2$2 -11] [c3$2 -11])
```

Rosette constructs: solve many with define-symbolic

solve searches for a binding of symbolic constants to concrete values that causes all assertions in expr to pass.

```
(define-symbolic id type)
(define-symbolic* id type)
```

```
(assert expr)
```

```
(verify expr)
(debug [type ...+] expr)
(solve expr)
(synthesize
  #:forall expr
  #:guarantee expr)
```

Solving same for multiple inputs: note the behavior of **define-symbolic**.

Can we repair fact on multiple inputs simultaneously?

```
(define (poly x)
 (+ (* x x x x) (* 6 x x x)
    (* 11 x x) (* 6 x)))

(define (fact x)
 (define-symbolic c1 c2 c3 integer?)
 (* (+ x c1) (+ x 1) (+ x c2) (+ x c3)))

(define (same p f x)
 (assert (= (p x) (f x))))


> (solve (begin
          (same poly fact -6)
          (same poly fact 12)))
(model [c1 2] [c2 3] [c3 0])
```

Rosette constructs: from solve to synthesize

Can we repair `fact` on all inputs as suggested by **solve**?

```
(define (poly x)
 (+ (* x x x x) (* 6 x x x)
    (* 11 x x) (* 6 x)))

(define (fact x)
 (define-symbolic c1 c2 c3 integer?)
 (* (+ x c1) (+ x 1) (+ x c2) (+ x c3)))

(define (same p f x)
 (assert (= (p x) (f x))))
```

```
(define-symbolic id type)
(define-symbolic* id type)
```

```
(assert expr)
```

```
(verify expr)
(debug [type ...+] expr)
(solve expr)
(synthesize
  #:forall expr
  #:guarantee expr)
```

Rosette constructs: synthesize

synthesize searches for a binding that causes all assertions in **#:guarantee** expr to pass for all bindings of the symbolic constants in the **#:forall** expr.

```
(define-symbolic id type)
(define-symbolic* id type)
```

```
(assert expr)
```

```
(verify expr)
(debug [type ...+] expr)
(solve expr)
(synthesize
  #:forall expr
  #:guarantee expr)
```

Can we repair fact on all inputs as suggested by **solve**?

```
(define (poly x)
 (+ (* x x x x) (* 6 x x x)
    (* 11 x x) (* 6 x)))

(define (fact x)
 (define-symbolic c1 c2 c3 integer?)
 (* (+ x c1) (+ x 1) (+ x c2) (+ x c3)))

(define (same p f x)
 (assert (= (p x) (f x))))


> (define-symbolic* i integer?)
> (synthesize
   #:forall i
   #:guarantee (same poly fact i))
```

Rosette constructs: synthesize

synthesize searches for a binding that causes all assertions in **#:guarantee** expr to pass for all bindings of the symbolic constants in the **#:forall** expr.

```
(define-symbolic id type)
(define-symbolic* id type)
```

```
(assert expr)
```

```
(verify expr)
(debug [type ...+] expr)
(solve expr)
(synthesize
  #:forall expr
  #:guarantee expr)
```

Yes! The solver finds concrete values for c1, c2, and c3 that work for every input i.

Can we repair `fact` on all inputs as suggested by **solve**?

```
(define (poly x)
 (+ (* x x x x) (* 6 x x x)
    (* 11 x x) (* 6 x)))

(define (fact x)
 (define-symbolic c1 c2 c3 integer?)
 (* (+ x c1) (+ x 1) (+ x c2) (+ x c3)))

(define (same p f x)
 (assert (= (p x) (f x))))


> (define-symbolic* i integer?)
> (synthesize
   #:forall i
   #:guarantee (same poly fact i))
(model [c1 3] [c2 0] [c3 2])
```

Rosette constructs: synthesize

synthesize searches for a binding that causes all assertions in **#:guarantee** expr to pass for all bindings of the symbolic constants in the **#:forall** expr.

```
(define-symbolic id type)
(define-symbolic* id type)
```

```
(assert expr)
```

```
(verify expr)
(debug [type ...+] expr)
(solve expr)
(synthesize
  #:forall expr
  #:guarantee expr)
```

To generate code, require the sketching library, save the module to a file, and issue a **synthesize** query.

Can we repair fact on all inputs as suggested by **solve**?

```
(require rosette/lib/synthax)

(define (poly x)
 (+ (* x x x x) (* 6 x x x)
    (* 11 x x) (* 6 x)))

(define (fact x)
 (* (+ x (??)) (+ x 1) (+ x (??)) (+ x (??))))

(define (same p f x)
 (assert (= (p x) (f x))))


> (define-symbolic* i integer?)
> (print-forms ; print the generated code
   (synthesize
    #:forall i
    #:guarantee (same poly fact i)))
```

Rosette constructs: synthesize

synthesize searches for a binding that causes all assertions in **#:guarantee** expr to pass for all bindings of the symbolic constants in the **#:forall** expr.

```
(define-symbolic id type)
(define-symbolic* id type)
```

```
(assert expr)
```

```
(verify expr)
(debug [type ...+] expr)
(solve expr)
(synthesize
  #:forall expr
  #:guarantee expr)
```

To generate code, require the sketching library, save the module to a file, and issue a **synthesize** query.

Can we repair fact on all inputs as suggested by **solve**?

```
(require rosette/lib/synthax)

(define (poly x)
 (+ (* x x x x) (* 6 x x x)
    (* 11 x x) (* 6 x)))

(define (fact x)
 (* (+ x 3) (+ x 1) (+ x 0) (+ x 2)))

(define (same p f x)
 (assert (= (p x) (f x))))


> (define-symbolic* i integer?)
> (print-forms ; print the generated code
   (synthesize
    #:forall i
    #:guarantee (same poly fact i)))
```

A programming model that integrates solvers into the language, providing constructs for program verification, synthesis, and more.

ROSETTE

Solver-aided programming in two parts: (1) getting started and (2) going pro

How to use a solver-aided language: the workflow, constructs, and **gotchas**.

How to build your own solver-aided tool via direct symbolic evaluation or language embedding.

Common pitfalls and gotchas

Reasoning precision

Unbounded loops

Unsafe features

"A gotcha is a valid construct in a system, program or programming language that works as documented but is counter-intuitive and almost invites mistakes because it is both easy to invoke and unexpected or unreasonable in its outcome."

—*Wikipedia*

Common pitfalls and gotchas: reasoning precision

Reasoning precision

Unbounded loops

Unsafe features

- Determines if integers and reals are approximated using k-bit words or treated as infinite-precision values.
- Controlled by setting `current-bitwidth` to an integer k > 0 or #f for approximate or precise reasoning, respectively.

Common pitfalls and gotchas: reasoning precision

Reasoning precision

Unbounded loops

Unsafe features

- Determines if integers and reals are approximated using k-bit words or treated as infinite-precision values.
- Controlled by setting `current-bitwidth` to an integer k > 0 or #f for approximate or precise reasoning, respectively.

```
; default current-bitwidth is #f
> (define-symbolic x integer?)
> (solve (assert (= x 64)))
```

Common pitfalls and gotchas: reasoning precision

Reasoning precision

Unbounded loops

Unsafe features

- Determines if integers and reals are approximated using k-bit words or treated as infinite-precision values.
- Controlled by setting `current-bitwidth` to an integer k > 0 or #f for approximate or precise reasoning, respectively.

```
; default current-bitwidth is #f
> (define-symbolic x integer?)
> (solve (assert (= x 64)))
(model [x 64])
```

Common pitfalls and gotchas: reasoning precision

Reasoning precision

Unbounded loops

Unsafe features

- Determines if integers and reals are approximated using k-bit words or treated as infinite-precision values.
- Controlled by setting `current-bitwidth` to an integer k > 0 or #f for approximate or precise reasoning, respectively.

```
; default current-bitwidth is #f
> (define-symbolic x integer?)
> (solve (assert (= x 64)))
(model [x 64])
> (verify (assert (not (= x 64))))
```

Common pitfalls and gotchas: reasoning precision

Reasoning precision

Unbounded loops

Unsafe features

- Determines if integers and reals are approximated using k-bit words or treated as infinite-precision values.
- Controlled by setting `current-bitwidth` to an integer k > 0 or #f for approximate or precise reasoning, respectively.

```
; default current-bitwidth is #f
> (define-symbolic x integer?)
> (solve (assert (= x 64)))
(model [x 64])
> (verify (assert (not (= x 64))))
(model [x 64])
```

Common pitfalls and gotchas: reasoning precision

Reasoning precision

Unbounded loops

Unsafe features

- Determines if integers and reals are approximated using k-bit words or treated as infinite-precision values.
- Controlled by setting `current-bitwidth` to an integer k > 0 or #f for approximate or precise reasoning, respectively.

```
; default current-bitwidth is #f
> (define-symbolic x integer?)
> (solve (assert (= x 64)))
(model [x 64])
> (verify (assert (not (= x 64))))
(model [x 64])

> (current-bitwidth 5)
> (solve (assert (= x 64)))
```

Common pitfalls and gotchas: reasoning precision

Reasoning precision

Unbounded loops

Unsafe features

- Determines if integers and reals are approximated using k-bit words or treated as infinite-precision values.
- Controlled by setting `current-bitwidth` to an integer k > 0 or #f for approximate or precise reasoning, respectively.

```
; default current-bitwidth is #f
> (define-symbolic x integer?)
> (solve (assert (= x 64)))
(model [x 64])
> (verify (assert (not (= x 64))))
(model [x 64])

> (current-bitwidth 5)
> (solve (assert (= x 64)))
(model [x 0])
> (verify (assert (not (= x 64))))
(model [x 0])
```

Common pitfalls and gotchas: unbounded loops

Reasoning precision

Unbounded loops

Unsafe features

- Loops and recursion must be *bounded* (aka *self-finitizing*) by
  - concrete termination conditions, or
  - upper bounds on size of iterated (symbolic) data structures.
- Unbounded loops and recursion run forever.

Common pitfalls and gotchas: unbounded loops

Reasoning precision

Unbounded loops

Unsafe features

- Loops and recursion must be *bounded* (aka *self-finitizing*) by
  - concrete termination conditions, or
  - upper bounds on size of iterated (symbolic) data structures.
- Unbounded loops and recursion run forever.

```
(define (search x xs)
  (cond
    [(null? xs) #f]
    [(equal? x (car xs)) #t]
    [else (search x (cdr xs))]))

> (define-symbolic xs integer? [5])
> (define-symbolic xl i integer?)
> (define ys (take xs xl))
> (verify
   (when (<= 0 i (- xl 1))
     (assert (search (list-ref ys i) ys))))
```

Common pitfalls and gotchas: unbounded loops

Reasoning precision

Unbounded loops

Unsafe features

- Loops and recursion must be *bounded* (aka *self-finitizing*) by
  - concrete termination conditions, or
  - upper bounds on size of iterated (symbolic) data structures.
- Unbounded loops and recursion run forever.

```
(define (search x xs)
  (cond
    [(null? xs) #f]
    [(equal? x (car xs)) #t]
    [else (search x (cdr xs))]))

> (define-symbolic xs integer? [5])
> (define-symbolic xl i integer?)
> (define ys (take xs xl))
> (verify
   (when (<= 0 i (- xl 1))
     (assert (search (list-ref ys i) ys))))
(unsat)
```

Terminates because `search` iterates over a bounded structure.

Common pitfalls and gotchas: unbounded loops

Reasoning precision

Unbounded loops

Unsafe features

- Loops and recursion must be *bounded* (aka *self-finitizing*) by
  - concrete termination conditions, or
  - upper bounds on size of iterated (symbolic) data structures.
- Unbounded loops and recursion run forever.

```
(define (factorial n)
  (cond
    [(= n 0) 1]
    [else (* n (factorial (- n 1)))]))
```

Common pitfalls and gotchas: unbounded loops

Reasoning precision

Unbounded loops

Unsafe features

- Loops and recursion must be *bounded* (aka *self-finitizing*) by
  - concrete termination conditions, or
  - upper bounds on size of iterated (symbolic) data structures.
- Unbounded loops and recursion run forever.

```
(define (factorial n)
  (cond
    [(= n 0) 1]
    [else (* n (factorial (- n 1)))]))

> (define-symbolic k integer?)
> (solve
    (assert (> (factorial k) 10)))
```

Common pitfalls and gotchas: unbounded loops

Reasoning precision

Unbounded loops

Unsafe features

- Loops and recursion must be *bounded* (aka *self-finitizing*) by
  - concrete termination conditions, or
  - upper bounds on size of iterated (symbolic) data structures.
- Unbounded loops and recursion run forever.

```
(define (factorial n)
  (cond
    [(= n 0) 1]
    [else (* n (factorial (- n 1)))]))

> (define-symbolic k integer?)
> (solve
    (assert (> (factorial k) 10)))
```

Unbounded because `factorial` termination depends on k.

Common pitfalls and gotchas: unbounded loops

Reasoning precision

Unbounded loops

Unsafe features

- Loops and recursion must be *bounded* (aka *self-finitizing*) by
  - concrete termination conditions, or
  - upper bounds on size of iterated (symbolic) data structures.
- Unbounded loops and recursion run forever.

Bound the recursion with a concrete guard.

```
(define (factorial n g)
  (assert (>= g 0))
  (cond
    [(= n 0) 1]
    [else (* n (factorial (- n 1) (- g 1)))]))
```

Common pitfalls and gotchas: unbounded loops

Reasoning precision

Unbounded loops

Unsafe features

- Loops and recursion must be *bounded* (aka *self-finitizing*) by
  - concrete termination conditions, or
  - upper bounds on size of iterated (symbolic) data structures.
- Unbounded loops and recursion run forever.

Bound the recursion with a concrete guard.

```
(define (factorial n g)
  (assert (>= g 0))
  (cond
    [(= n 0) 1]
    [else (* n (factorial (- n 1) (- g 1)))]))

> (define-symbolic k integer?)
> (solve
    (assert (> (factorial k 3) 10)))
```

Common pitfalls and gotchas: unbounded loops

Reasoning precision

Unbounded loops

Unsafe features

- Loops and recursion must be *bounded* (aka *self-finitizing*) by
  - concrete termination conditions, or
  - upper bounds on size of iterated (symbolic) data structures.
- Unbounded loops and recursion run forever.

Bound the recursion with a concrete guard.

```
(define (factorial n g)
  (assert (>= g 0))
  (cond
    [(= n 0) 1]
    [else (* n (factorial (- n 1) (- g 1)))]))

> (define-symbolic k integer?)
> (solve
    (assert (> (factorial k 3) 10)))

(unsat)
```

UNSAT because the bound is too small to find a solution.

Common pitfalls and gotchas: unbounded loops

Reasoning precision

Unbounded loops

Unsafe features

- Loops and recursion must be *bounded* (aka *self-finitizing*) by
  - concrete termination conditions, or
  - upper bounds on size of iterated (symbolic) data structures.
- Unbounded loops and recursion run forever.

Bound the recursion with a concrete guard.

```
(define (factorial n g)
  (assert (>= g 0))
  (cond
    [(= n 0) 1]
    [else (* n (factorial (- n 1) (- g 1)))]))

> (define-symbolic k integer?)
> (solve
    (assert (> (factorial k 4) 10)))

(model
  [k 4])
```

Make sure the bound is large enough …

Common pitfalls and gotchas: unsafe features

Reasoning precision

Unbounded loops

Unsafe features

- Rosette *lifts* only a core subset of Racket to operate on symbolic values. This includes all constructs in `#lang rosette/safe`
- Unlifted constructs can be used in `#lang rosette` but require care: the programmer must determine when it is okay for symbolic values to flow to unlifted code.

Common pitfalls and gotchas: unsafe features

Reasoning precision

Unbounded loops

Unsafe features

- Rosette *lifts* only a core subset of Racket to operate on symbolic values. This includes all constructs in `#lang rosette/safe`
- Unlifted constructs can be used in `#lang rosette` but require care: the programmer must determine when it is okay for symbolic values to flow to unlifted code.

```
; vectors are lifted
> (define v (vector 1 2))
> (define-symbolic k integer?)
> (vector-ref v k)
```

Common pitfalls and gotchas: unsafe features

Reasoning precision

Unbounded loops

Unsafe features

- Rosette *lifts* only a core subset of Racket to operate on symbolic values. This includes all constructs in `#lang rosette/safe`
- Unlifted constructs can be used in `#lang rosette` but require care: the programmer must determine when it is okay for symbolic values to flow to unlifted code.

```
; vectors are lifted
> (define v (vector 1 2))
> (define-symbolic k integer?)
> (vector-ref v k)
(ite* (⊢ (= 0 k) 1) (⊢ (= 1 k) 2)))
```

Common pitfalls and gotchas: unsafe features

Reasoning precision

Unbounded loops

Unsafe features

- Rosette *lifts* only a core subset of Racket to operate on symbolic values. This includes all constructs in `#lang rosette/safe`
- Unlifted constructs can be used in `#lang rosette` but require care: the programmer must determine when it is okay for symbolic values to flow to unlifted code.

```
; vectors are lifted
> (define v (vector 1 2))
> (define-symbolic k integer?)
> (vector-ref v k)
(ite* (⊢ (= 0 k) 1) (⊢ (= 1 k) 2)))

; hashes are unlifted
> (define h (make-hash '((0 . 1)(1 . 2))))
> (hash-ref h k)
```

Common pitfalls and gotchas: unsafe features

Reasoning precision

Unbounded loops

Unsafe features

- Rosette *lifts* only a core subset of Racket to operate on symbolic values. This includes all constructs in `#lang rosette/safe`
- Unlifted constructs can be used in `#lang rosette` but require care: the programmer must determine when it is okay for symbolic values to flow to unlifted code.

```
; vectors are lifted
> (define v (vector 1 2))
> (define-symbolic k integer?)
> (vector-ref v k)
(ite* (⊢ (= 0 k) 1) (⊢ (= 1 k) 2)))

; hashes are unlifted
> (define h (make-hash '((0 . 1)(1 . 2))))
> (hash-ref h k)
hash-ref: no value found for key
  key: k
```

Common pitfalls and gotchas: unsafe features

Reasoning precision

Unbounded loops

Unsafe features

- Rosette *lifts* only a core subset of Racket to operate on symbolic values. This includes all constructs in `#lang rosette/safe`
- Unlifted constructs can be used in `#lang rosette` but require care: the programmer must determine when it is okay for symbolic values to flow to unlifted code.

```
; vectors are lifted
> (define v (vector 1 2))
> (define-symbolic k integer?)
> (vector-ref v k)
(ite* (⊢ (= 0 k) 1) (⊢ (= 1 k) 2)))

; hashes are unlifted
> (define h (make-hash '((0 . 1)(1 . 2))))
> (hash-ref h k)
hash-ref: no value found for key
  key: k
> (hash-set! h k 3)
> (hash-ref h k)
```

Common pitfalls and gotchas: unsafe features

Reasoning precision

Unbounded loops

Unsafe features

- Rosette *lifts* only a core subset of Racket to operate on symbolic values. This includes all constructs in `#lang rosette/safe`
- Unlifted constructs can be used in `#lang rosette` but require care: the programmer must determine when it is okay for symbolic values to flow to unlifted code.

```
; vectors are lifted
> (define v (vector 1 2))
> (define-symbolic k integer?)
> (vector-ref v k)
(ite* (⊢ (= 0 k) 1) (⊢ (= 1 k) 2)))

; hashes are unlifted
> (define h (make-hash '((0 . 1)(1 . 2))))
> (hash-ref h k)
hash-ref: no value found for key
  key: k
> (hash-set! h k 3)
> (hash-ref h k)
3
```

A programming model that integrates solvers into the language, providing constructs for program verification, synthesis, and more.

ROSETTE

emina.github.io/rosette/

Solver-aided programming in two parts: (1) **getting started** and (2) going pro

How to use a solver-aided language: the workflow, constructs, and gotchas.

How to build your own solver-aided tool via direct symbolic evaluation or language embedding.

Summary

Today

- Course overview & logistics
- Getting started with solver-aided programming

Next lecture

- Going pro with solver-aided programming